REPORT DOCUMENTATION PAGE

Form Approved
OMB NO. 0704-0188

1. AGENCY USE ONLY (Leave Blank)	2. REPORT DATE 30 August 04	3. REPORT TYPE AND DATES COVERED Final Report 01 Jun 01 - 31 May 04

4. TITLE AND SUBTITLE
Well-Conditioned Multi-Level Fast Multipole Modeling of Military Communication Channels

5. FUNDING NUMBERS
DAAD19-01-1-0565

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8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

U. S. Army Research Office
P.O. Box 12211
Research Triangle Park, NC 27709-2211

10. SPONSORING / MONITORING AGENCY REPORT NUMBER

41693.2-EL

11. SUPPLEMENTARY NOTES
The views, opinions and/or findings contained in this report are those of the author(s) and should not be construed as an official Department of the Army position, policy or decision, unless so designated by other documentation.

12 a. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution unlimited.

12 b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Duke University and Virginia Polytechnic Institute and State University (VPI&SU) propose to team in a research effort to develop computer codes for the analysis and prediction of electromagnetic wave propagation over terrain. Those features of the terrain to be included are geographic scales of surface elevation, surface roughness, variable electrical constitutive properties, and vegetation cover (e.g. single and multiple trees). The frequencies to be considered comprise those of greatest interest to the U.S. Army in their current and projected communications and remote sensing needs. The approach will focus on the solution of appropriate integral equations describing the interaction of the EM waves and the terrain. Both institutions will work on developing the most appropriate integral equations to describe generic propagation scenarios. In the numerical solution of these integral equations, VPI&SU will concentrate on preconditioning or renormalizing them so as to minimize the number of iterations necessary to solve them to a given level of accuracy. Duke will focus on developing improved fast solvers for the preconditioned equations based upon their previous work with the Multi-Level Fast Multipole Algorithm (MLFMA). Both organizations will also attempt to keep the developed methods and codes general to the extent that they may also be applied to propagation in an urban environment. The rigorous, well-conditioned MLFMA models will be used as benchmarks to calibrate the accuracy of traditional electromagnetic-propagation models, including ray, beam and parabolic-equation (PE) solvers.

14. SUBJECT TERMS
MLFMA, scattering

15. NUMBER OF PAGES

16. PRICE CODE

17. SECURITY CLASSIFICATION OR REPORT	18. SECURITY CLASSIFICATION ON THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

NSN 7540-01-280-5500

Standard Form 298 (Rev.2-89)
Prescribed by ANSI Std. 239-18
298-102

I. Statement of the Problem

With the increased demand for wireless technology, there is a growing need for fast and accurate prediction models. Until recently propagation models were usually based on approximate methods, especially if a relatively large number of predictions are required. For example, radio-wave propagation in foliage has been modeled using an equivalent lossy dielectric layer situated above the earth. For frequencies up to UHF, Sarabandi *et al.* [3,4] have proposed a hybrid analytical and numerical approach that accounts for multiple scattering among tree trunks and includes the effects of the forest ground plane.

For modern personal communication systems, the typical frequency range is from 800 MHz to 2 GHz. At these frequencies the tree trunks in a forest are electrically very large, allowing high-frequency electromagnetic analysis methods. Several prediction models based on analytical ray tracing and the uniform theory of diffraction (UTD) have been reported in the literature. However, most of these models are designed for propagations in an urban environment, which undergoes different propagation and scattering mechanisms from those found in forests.

The ray models employ high-frequency approximations, and therefore it has only been very recently that rigorous models have become sufficiently efficient computationally such that they can be used for validation. A comparison between ray methods and rigorous models, with application to in-forest propagation, is the principal contribution of this correspondence. We have developed a multi-level fast-multiple algorithm (MLFMA) for general conducting and dielectric targets in the presence of a half-space. With this multi-target MLFMA, we may generate benchmark numerical results, with which we can validate ray-tracing models.

II. Scientific Progress and Accomplishments

Over the last several years the fast multipole model (FMM) has been employed to yield marked improvements in the computational power of electromagnetic models. In particular, the FMM has been applied to problems that previously have been solved via techniques such as the method of moments (MoM). The MoM has been widely applied to the solution of electric, magnetic and combined-field surface-integral equations (EFIE, MFIE and CFIE, respectively). While the MoM is in principle applicable to targets of arbitrary shape and size, computational resources typically limit the range of problems for which it can be applied. In this context, if N unknowns are employed in the MoM formulation, the MoM solution requires order N^2 memory (RAM) to store the matrix equation, order N^2 computational complexity (CPU time) to fill the matrix, and order N^3 or PN^2 CPU time to solve the matrix equation (N^3 for an LU-decomposition solution and PN^2 for a conjugate-gradient (CG) type solution, where P represents the number of CG iterations). As the target size increases relative to wavelength, the commensurate increase in N substantially restricts the utility of MoM solutions. By contrast, the FMM integral-equation solution requires order $N^{3/2}$ memory and order $PN^{3/2}$ CPU time, while an MLFMA requires respectively order $N \log N$ and $PN \log N$. This implies that the FMM and MLFMA formulations allow consideration of scattering from targets of electrical size well beyond what is possible with the MoM.

The FMM and MLFMA have been applied to the analysis of scattering from electrically large and complex targets. However, these models have previously been applied primarily to scattering from free-space targets. In addition, there has been application of the FMM to problems involving planar conducting structures in thin stratified layers, through exploitation of an asymptotic form of the layered-medium Green's function. The FMM and MLFMA have also been extended to arbitrarily shaped conducting targets above or below a half space. Further, the MLFMA has recently been extended to the case of general dielectric targets in free space.

In the work pursued this past year, we combined algorithmic concepts considered separately in previous work - namely the half-space problem and scattering from dielectric targets - to develop an MLFMA for general dielectric targets above or below a lossy half space. For the "near" MLFMA terms the complete dyadic half-space Green's function is evaluated rigorously via the complex-image technique, for electric and magnetic current sources. An approximate asymptotic form of the Green's function is applied for the "far" MLFMA interactions, although we have demonstrated that this approximate formulation yields highly accurate results, with computational efficiency. Scattering from the dielectric target is treated using a traditional formulation employing electric and magnetic surface currents, with a solution based on the widely used Rao, Wilton, Glisson (RWG) basis functions.

III. Technology Transfer

The MLFMA models developed under this program have been delivered to Dr. Anders Sullivan at the Army Research Laboratory, Adelphi, MD.

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